DESIGN, DEVELOPMENT AND CONTROL OF SOLAR PV-WIND DRIVEN DFIG BASED MICROGRIDS

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DESIGN, DEVELOPMENT AND CONTROL OF SOLAR PV-WIND DRIVEN DFIG BASED MICROGRIDS

by

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Dedicated
to

My Guru and Beloved Lord Shri Jagannath

CERTIFICATE

It is certified that the thesis entitled "**Design, Development and Control of Solar PV-Wind Driven DFIG based Microgrids**" being submitted by **Mr. Sandeep Kumar Sahoo** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of my other degree or diploma.

Dated:

(Prof. Bhim Singh)
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Sandeep Kumar Sahoo

ABSTRACT

The objective of this research is to design, control, and implement microgrid systems integrating solar photovoltaic (PV) array with battery energy storage (BES) and wind energy with BES. Double stage three phase three wire and three phase four wire solar PV-BES based microgrids are implemented in this work. Three-phase four-wire microgrids offer neutral current compensation in addition to the functionalities of three-phase three-wire PV-BES microgrids. Doubly fed induction generator (DFIG) is preferred in wind energy conversion system (WECS) due to its variable speed operation, partial-scale power converter (reducing cost), independent active/reactive power control and higher efficiency compared to full-converter systems. So, in this work, wind driven DFIG-BES based DG set/grid interactive microgrids are explored.

This work investigates a cost-effective mechanical speed and position sensorless control for DFIG-wind energy conversion system (WECS). A sensorless technique based on an adaptive notch filter (ANF) with a position compensation unit (PCU) is proposed for DFIG. It operates efficiently under varying wind speeds and load imbalances. Despite the presence of harmonics in rotor currents, proposed scheme ensures precise rotor speed estimation. Additionally, PCU corrects position errors, ensuring accurate rotor position estimation.

Frequent power outages in rural areas demand reliable and efficient energy solutions. To tackle this, autonomous and intelligent control strategies are developed for grid-interactive PV-BES and wind-BES microgrids. These systems ensure uninterrupted power during grid failures and subsequent restorations while managing renewable power fluctuations. The microgrid operates seamlessly across different modes, with smooth transition logic and islanding detection enabling shifts between off-grid and grid-connected modes. In off-grid operation, the grid-forming converter (GFC) maintains voltage and frequency stability at the point of common interconnection (PCI). During grid/DG-connected mode, advanced GFC control techniques improve power quality by extracting fundamental positive-sequence currents from nonlinear loads. These systems also provide power quality enhancements-such as harmonic elimination, power factor correction, reactive power compensation, and grid currents balancing-while ensuring continuous power to critical loads, even during grid outages.

सारांश

इस शोध का उद्देश्य सौर फोटोवोल्टिक (PV) सरणी को बैटरी ऊर्जा संचयन (BES) के साथ और पवन ऊर्जा को BES के साथ एकीकृत करने वाले माइक्रोग्रिड सिस्टम को डिजाइन, नियंत्रित और कार्यान्वित करना है। इस कार्य में दो-चरण वाले तीन-फेज तीन-तार और तीन-फेज चार-तार सौर PV-BES आधारित माइक्रोग्रिड्स को लागू किया गया है। तीन-फेज चार-तार माइक्रोग्रिड्स, तीन-फेज तीन-तार PV-BES माइक्रोग्रिड्स की कार्यक्षमताओं के अतिरिक्त, न्यूट्रल करंट कम्पेंसेशन भी प्रदान करते हैं। पवन ऊर्जा रूपांतरण प्रणाली (WECS) में डब्ल्यू फेड इंडक्शन जनरेटर (DFIG) को चर गति संचालन, आंशिक-स्केल पावर कन्वर्टर (लागत कम करना), स्वतंत्र सक्रिय/प्रतिक्रियाशील शक्ति नियंत्रण और पूर्ण-कन्वर्टर सिस्टम्स की तुलना में उच्च दक्षता के कारण प्राथमिकता दी जाती है। इसलिए, इस कार्य में पवन चालित DFIG-BES आधारित DG सेट/ग्रिड इंटरएक्टिव माइक्रोग्रिड्स का अन्वेषण किया गया है।

इस कार्य में DFIG-पवन ऊर्जा रूपांतरण प्रणाली (WECS) के लिए एक लागत-प्रभावी यांत्रिक गति और पोजीशन सेंसरलेस नियंत्रण की जांच की गई है। DFIG के लिए एक पोजीशन कम्पेंसेशन यूनिट (PCU) के साथ एडाप्टिव नॉच फिल्टर (ANF) पर आधारित सेंसरलेस तकनीक प्रस्तावित की गई है। यह परिवर्तनशील पवन गति और लोड असंतुलन की स्थिति में कुशलतापूर्वक कार्य करती है। रोटर धाराओं में हार्मोनिक्स की उपस्थिति के बावजूद, प्रस्तावित योजना रोटर गति का सटीक अनुमान सुनिश्चित करती है। साथ ही, PCU पोजीशन त्रुटियों को सही करता है, जिससे रोटर पोजीशन का सही अनुमान लगाया जा सकता है।

ग्रामीण क्षेत्रों में बार-बार होने वाली बिजली कटौती के कारण विश्वसनीय और कुशल ऊर्जा समाधानों की आवश्यकता है। इस समस्या से निपटने के लिए, ग्रिड-इंटरएक्टिव PV-BES और पवन-BES माइक्रोग्रिड्स के लिए स्वायत्त और बुद्धिमान नियंत्रण रणनीतियाँ विकसित की गई हैं। ये सिस्टम ग्रिड विफलताओं और उसके बाद की बहाली के दौरान अबाधित बिजली प्रदान करते हुए नवीकरणीय ऊर्जा उतार-चढ़ाव का प्रबंधन करते हैं। माइक्रोग्रिड विभिन्न मोड्स में निर्बाध रूप से कार्य करता है, जिसमें सुगम संक्रमण लॉजिक और आइलैंडिंग डिटेक्शन ऑफ-ग्रिड और ग्रिड-कनेक्टेड मोड्स के बीच परिवर्तन को सक्षम करते हैं। ऑफ-ग्रिड संचालन में, ग्रिड-फॉर्मिंग कन्वर्टर (GFC) पॉइंट ऑफ कॉमन इंटरकनेक्शन (PCI) पर वोल्टेज और आवृत्ति स्थिरता बनाए रखता है। ग्रिड/DG-कनेक्टेड मोड के दौरान, उन्नत GFC नियंत्रण तकनीकें गैर-रैखिक भारों से मूलभूत पॉजिटिव-सीक्वेंस धाराओं को निकालकर विद्युत गुणवत्ता में सुधार करती हैं। ये सिस्टम हार्मोनिक्स उन्मूलन, पावर फैक्टर सुधार, प्रतिक्रियाशील शक्ति क्षतिपूर्ति और ग्रिड धाराओं को संतुलित करने जैसी विद्युत गुणवत्ता वृद्धि भी प्रदान करते हैं, साथ ही ग्रिड आउटेज के दौरान भी महत्वपूर्ण भारों को निरंतर बिजली सुनिश्चित करते हैं।

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LIST OF ABBREVIATIONS

3P4W	Three-phase four-wire
ADC	Analog to digital converter
ADT	Active detection technique
AECCF-PLL	Adaptive enhanced complex coefficient filter-phase locked loop
AI	Artificial intelligence
ANF	Adaptive notch filter
BES	Battery energy storage
BESS	Battery energy storage systems
CERTS	Consortium for Electric Reliability Technology Solutions
CLMS	Cascaded least mean squares
DERs	Distributed energy resources
DFIG	Doubly fed induction generator
DG	Diesel generator
DGM	DG set mode control
DGS	DG set synchronization
DIO	Digital input/output
DSO	Digital storage oscilloscopes
DSP	Digital signal processor
DSTATCOM	Distribution static compensator
EHCRA	Exponential hyperbolic cosine robust adaptive
EIA	Energy Information Administration
FC	Forward compensation
FEZ	Fuel economic zone
FOC	Field oriented control
FRT	Fault ride-through
GFC_p	Grid forming converter used in PV-BES based microgrid
GFCs	Grid-forming converters
GFC_w	Grid forming converter used in wind-BES based microgrid
GFL	Grid-following
GFM	Grid forming
GMC	Grid mode control
GMCC	Generalized MCC
GS	Grid synchronization
HBC	Hysteresis based control
HCS	Hill Climbing Search
HFSI	High frequency signal injection
HIL	Hardware-in-the-loop
HVDC	High-voltage direct current
IGBT	Insulated Gate Bipolar Transistor
IMC	Islanded mode control
INC	Incremental conductance
IT	Information technology
KMCC	Kernel MCC
LF	Loop filter
LHCA	Hyperbolic cosine function-based algorithms like logarithmic hyperbolic cosine adaptive
Llncosh	Least lncosh
LMAT	Least mean absolute third
LMF	Least mean fourth

LMS	Least mean square
LMSEF	Least mean square with an exponential function
LNF-MPC	Lawson-Norm adaptive filter-based model predictive control
LPF	Low pass filter
MCB	Miniature circuit breaker
MCC	Maximum correntropy criterion
MGs	Microgrids
MLMS	Modified LMS
MPC	Model predictive control
MPSMC	Model predictive and sliding mode control
MRAOs	Model reference adaptive observers
NDZ	Non-Detection Zone
OFOMAVSS-LMS	Optimized fractional order modified adaptive variable step size LMS
OPAMP	Operational Amplifier
OTSR	Optimal tip speed ratio
P&O	Perturb and observe
PCB	Printed circuit board
PCI	Point of common interconnection
PCU	Position compensation unit
PES_{dg}	DG set power electronics switch
PES_{g}	Grid power electronics switch
PES_{s}	Stator power electronics switch
PI	Proportional-integral
PLLs	Phase-locked loops
PMSG	Permanent magnet synchronous generator
PNSC	Positive negative sequence components
PPFs	Passive power filters
PPP	Peak power point
PPPT	Peak power point tracking
PQ	Power quality
PSC	PCI side converter
PSF	Power Signal Feedback
PSV	Positive sequence voltage
PV	Photovoltaic
PV-BES	Photovoltaic-battery energy storage
PVFFC	PV feed forward component
q-LMF	quantum calculus-least mean fourth
RESs	Renewable energy sources
RPLL	Rotor phase locked loop
RSC	Rotor side converter
SCIM	Squirrel cage induction machine
SOC	State-of-charge
SOGI	Second order generalized integrator
SRF	Synchronous reference frame
SS	Stator synchronization
SSDG	Status signal of DG set
SSG	Status signal of grid
SSS	Status signal of stator
T2FCSRF-PLL	Type 2-Forward compensation synchronous reference frame phase locked loop

T2SRF-PLL	Type-2 synchronous reference frame phase-locked loop
T3MSOGI	Type-3 modified second order generalized integrator
THD	Total harmonic distortion
UEHCRA	Updated exponential hyperbolic cosine robust adaptive
UPF	Unity power factor
UPS	Uninterruptible power supplies
VCO	Voltage controlled oscillator
VFB	Voltage filtering block
VSCs	Voltage source converters
VSI	Voltage-source inverter
VSSMLMS	Variable step size modified least mean square
VST-LMS	Variable sparsity with two least mean square
WECS	Wind energy conversion system
Wind-BES	Wind-battery energy storage
WOVSSA	Weight optimized variable step size adaptive
WRIG	Wound rotor induction generator
WT	Wind turbine
WVSSV	Wiener variable step size with variance smoothening

LIST OF SYMBOLS

V_{pp}	Peak value PCI voltage
V_{gp}	Peak value of utility voltage
V_{sp}	Peak value of stator voltages
V_{dgp}	Peak value of DG set voltages
v_{gab}, v_{gbc}	Line-line voltages of grid
v_{dgab}, v_{dgbc}	Line-line voltages of DG set
v_{sab}, v_{sbc}	Line-line voltages of stator
v_{ga}, v_{gb}, v_{gc}	Phase voltages of grid
v_{sa}, v_{sb}, v_{sc}	Phase voltages of stator
v_{dga}, v_{dgb}, v_{dgc}	Phase voltages of DG set
i_{ga}, i_{gb}, i_{gc}	Sensed grid currents
i_{ga}^*, i_{gb}^*, i_{gc}^*	Reference grid currents
i_{La}, i_{Lb}, i_{Lc}	Sensed load currents
i_{dga}, i_{dgb}, i_{dgc}	Sensed DG set currents
i_{dga}^*, i_{dgb}^*, i_{dgc}^*	Reference DG set currents
i_{ra1}, i_{rb1}, i_{rc1}	Sensed rotor currents of DFIG prior to stator synchronization
i_{ra1}^*, i_{rb1}^*, i_{rc1}^*	Reference rotor currents of DFIG prior to stator synchronization
i_{ra2}, i_{rb2}, i_{rc2}	Sensed rotor currents of DFIG post stator synchronization
i_{ra2}^*, i_{rb2}^*, i_{rc2}^*	Reference rotor currents of DFIG post stator synchronization
i_{sa}, i_{sb}, i_{sc}	Sensed stator currents DFIG
f_g	Frequency of grid voltages
f_s	Frequency of stator voltages
f_{dg}	Frequency of DG set voltages
Θ_p	Angle of PCI voltages
Θ_g	Angle of grid voltages
Θ_s	Angle of stator voltages
Θ_{dg}	Angle of DG set voltages
v_{LL1}	Line-line voltage of solar PV-BES based microgrid
v_{LL2}	Line-line voltage of wind-BES based microgrid
V_{dc1}	DC bus voltage of GFC_p
C_{dc1}	DC bus capacitor of GFC_p
P_L	Real power delivered to load
Q_L	Reactive power delivered to load
V_{oc}	Open circuit voltage of PV array
I_{sc}	Short circuit current of PV array
V_{ppp}	PPP voltage of PV array
I_{ppp}	PPP current of PV array
P_{pv}	PV array's power output
P_{ppp}	PPP power
W_{pv}	PV array feed forward component
V_b	BES voltage
I_b	BES current
P_b	BES power
D_b	Duty ratio of the boost converter
L	Inductor of the boost converter
L_{f1}	Interfacing inductor of GFC_p
L_{f1n}	Interfacing inductor of fourth leg of GFC_p
R_f, C_f	RC filter
V_{pp}^*	Reference value of PCI peak voltage

u_{pa}, u_{pb}, u_{pc}	Unit templates of grid voltages
$v_{pa}^*, v_{pb}^*, v_{pc}^*$	Reference PCI voltages
$\Delta\Theta, \Delta\omega$	Difference between angles and angular frequency of the phase angle matching block to synchronize PCI to grid
K_{fp}, K_{fi}	Proportional and integral gains of the PI controller used for angle matching
$V_{pd}^*, V_{pq}^*, V_{p0}^*$	Reference values of d axis, q axis and zero axis voltages of PCI
V_{pd}, V_{pq}, V_{p0}	Sensed values of d axis, q axis and zero axis voltages of PCI
V_{pde}, V_{pqe}, V_{0e}	Errors between reference and sensed values of d axis, q axis and zero axis voltages of PCI
i_{c1abc}	Sensed GFC_p currrents
i_{c1abc}^*	Reference GFC_p currrents
I_{c1dq0}^*	d axis, q axis and zero axis components of reference GFC_p currents
i_{c2abc}	Sensed GFC_w currrents
i_{c2abc}^*	Reference GFC_w currrents
I_{c2dq}^*	d and q axis components of reference GFC_w currents
i_{Ln}, i_{c1n}, i_{gn}	Neutral currents of load, GFC_p and grid
i_{gne}	Error between reference and sensed grid neutral currents
V_{dc2}	DC bus voltage of DFIG
V_{dc2}^*	Reference DC bus voltage of DFIG
V_{dce}	Error between reference and sensed DC bus voltages of DFIG
K_{dcp}, K_{dci}	Proportional and integral gains of PI controllers for controlling DC bus of DFIG
i_{psabc}	PSC currents
I_{psd}, I_{psq}	Sensed PSC dq axis voltages
I_{psd}^*, I_{psq}^*	Reference PSC dq axis voltages
I_{psde}, I_{psqe}	Errors between reference and sensed PSC dq axis currents
K_{psp}, K_{psi}	Proportional and integral gains of PI controllers for inner current loop control of PSC of DFIG
V_{GFCp_IGBT}	Voltage rating of IGBT of GFC_p
I_{GFCp_IGBT}	Current rating of IGBT of GFC_p
f_{s_GFCp}	Switching frequency of GFC_p
K_{sf}	Safety factor of GFC_p
V_{GFCw_IGBT}	Voltage rating of IGBT of GFC_w
I_{GFCw_IGBT}	Current rating of IGBT of GFC_w
f_{s_GFCw}	Switching frequency of GFC_w
V_{PSC_IGBT}	Voltage rating of IGBT of PSC
I_{PSC_IGBT}	Current rating of IGBT of PSC
f_{s_PSC}	Switching frequency of PSC
V_{RSC_IGBT}	Voltage rating of IGBT of RSC
I_{RSC_IGBT}	Current rating of IGBT of RSC
P_{GFC_p}	Real power rating of GFC_p
S_{GFC_p}	KVA rating of GFC_p
P_{GFC_w}	Real power rating of GFC_w
Q_{GFC_w}	Reactive power rating of GFC_w
S_{GFC_w}	KVA rating of GFC_w
P_{PSC}	Real power rating of PSC
Q_{PSC}	Reactive power rating of PSC
S_{PSC}	KVA rating of PSC
P_{RSC}	Real power rating of RSC
Q_{RSC}	Reactive power rating of RSC

S_{RSC}	KVA rating of PSC
W_a, W_b, W_c	Fundamental active weights of the load currents extracted using WVSSV control
W_{La}	Equivalent weight of load currents extracted using WVSSV control
e	Mean square error
μ, β, ε *and* $€_p$	Step factors of, acceleration, step size and acceleration factor of WVSSV filter
$I_{pLa}, I_{pLb}, I_{pLc}$	Fundamental active weights of the load currents extracted using VSSMLMS control
I_{pLt}	Equivalent weight of load currents extracted using VSSMLMS control
$K(x)$	Step size of VSSMLMS filter
P_m	Mechanical power of the wind turbine
ρ	Air density
r	radius of the wind turbine
V_w	Wind velocity
C_p	Power coefficient of the wind turbine
λ	Optimal tip speed ratio
ω_t	Rotational speed of the wind turbine
N	Gear ratio
P_s, P_r	Real power delivered by the stator and rotor of the DFIG
P_{dfig}	Net power delivered by the DFIG
Q_s	Reactive power delivered by stator of DFIG
Q_e	Error between reference and actual reactive power delivered by stator of DFIG
V_{sf}	Voltage safety factor
I_{sf}	Current safety factor
h	Overload factor
m_i	Modulation index
s_m	Maximum operating slip of DFIG
L_g	Interfacing inductor of PSC
L_{f2}	Interfacing inductor of GFC_w
ω_{i/p_ANF}	Input frequency of ANF
ω_r	Angular speed of rotor of DFIG in rad/s
ω_r^*	Reference angular speed of rotor of DFIG in rad/s
ω_{rest}	Estimated angular speed of rotor in rad/s
ω_p	Angular frequency of PCI
i_{rDQ}	Rotor currents in DQ reference frame
$i_{r\alpha\beta}$	Rotor currents in $\alpha\beta$ reference frame
I_{rdq2}	Rotor currents of DFIG in dq frame post stator synchrnization
I_{rdq2}^*	Reference rotor currents of DFIG in dq frame post stator synchrnization
$V_{s\alpha\beta}^+$	Filtered 2ph stator voltages
V_{sd}^*, V_{sq}^*	Reference stator voltages in dq frame
V_{sdest}	Estimated d-axis stator voltage in dq frame
R_s	Stator resistance of DFIG
L_m	Mutual inductance between stator and rotor winding of DFIG
I_{sq}	q axis current of stator of DFIG
I_{rq}	q axis current of rotor of DFIG
Θ_r	Rotor position of DFIG
Θ_{rest}	Estimated rotor position of DFIG

Θ_{PC}	Position compensation for DFIG
$\Theta_r^{'}$	Intermediate estimated position of DFIG
$K_{ir\Theta}$	Integral gain of RSC controller prior to stator synchronization
K_{pr5}, K_{ir5}	Proportional and integral gains of PI controllers for inner current loops control of RSC of DFIG post stator synchronization
K_{pr4}, K_{ir4}	Proportional and integral gains of PI controllers for outer speed control of RSC of DFIG post stator synchronization
K_{pr2}, K_{ir2}	Proportional and integral gains of PI controllers for reactive power control of RSC of DFIG post stator synchronization
K_{pa}, K_{ia}	Proportional and integral gains of PI controller used in VCO of AECCF PLL
G_{pa}, G_{pb}, G_{pc}	Fundamental active weights of the load currents extracted using WOVSSA filter control
G_{pt}	Mean of active power weights of load currents estimated using WOVSSA filter control
P_g^*	Reference grid power
G_g	Net active weight component of grid current
i_{labcf}	Fundamental component of nonlinear load currents extracted using WOVSSA filter control
P	Number of optimized weights used for filtering
Z	Number of weights used for optimization
$\psi(k)$	Cost function of LMF filter
ζ	Variable step size for WOVSSA filter
$\mu_{l,j}(k)$	Interim step size of WOVSSA filter
$\rho_{l,j}(k)$	Cost function of interim step size
$C_{l,j}(k)$	Interim estimated weight
K_{pp}, K_{ip}	Proportional and integral gains of PI controller used in VCO of T2FCSRF-PLL
ξ	Damping factor
F_{La}, F_{Lb}, F_{Lc}	Fundamental active weights of the load currents extracted using UEHCRA filter control
F_{Lt}	Mean of active power weights of load currents estimated using UEHCRA filter control
σ	Scaling factor
η	Shaping parameter
u_{dgabc}	Unit templates of DG set voltages